Erosion Potential in Private Forested Watersheds

of Northern California:

A GIS Model

Prepared for the California Department of Forestry and Fire Protection
Under Interagency Agreement 8 CA17097#2

by

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with assistance from the U.S. Geological Survey
Under Standard Agreement #1093-214

March 1994

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INTRODUCTION

Timber harvesting is a major land management practice that can affect hillslope stability. Erosion resulting from timber harvesting activities can increase sediment yields 4 to 78 times that of natural forest conditions (Megahan and others, 1978; Bishop and Stevens, 1964; Morrison, 1975). Erosion and sediment production can have long-term impacts on timber site productivity, fish habitat, reservoir storage capacity, and domestic water supplies (Reid and Dunne, 1984; Brown, 1975). With these concerns in mind, the California Department of Forestry and Fire Protection (CDF) contracted with the Department of Conservation's Division of Mines and Geology (DMG) to develop a semi-quantitative method to delineate those forested watersheds which are most susceptible to erosion when hillslopes are disturbed by timber harvest operations.

Intrinsic erosion potential was modeled on private and state-owned commercial timberlands regulated by CDF. The goal was to select the most significant factors controlling erosion that could be delineated consistently over large areas. The effects of forest land management on erosion vary spatially because of differences in climate, geologic materials, vegetative cover, and topography. Therefore all areas are not equally sensitive to a particular forest practice.

A Geographic Information System (GIS) model was developed to prioritize the relative susceptibility of forested watersheds to erosion. A combination of the most significant geomorphic factors which contribute to the driving and resisting forces controlling landscape denudation -- material strength, slope, and precipitation -- were used to delineate areas most prone to increases in sediment yield.

Most erosion and sedimentation studies heretofore have been limited to the evaluation of local conditions at individual harvest sites or within small hydrologic basins (Sommarstrom and others, 1990; California Department of Water Resources, 1979; Kelsey, 1977). In contrast this study is a regional evaluation of erosion potential based on semi-quantitative analyses.

The purpose of the investigation was to develop a quantitative method for ranking erosion risks based on available geomorphic data and check this system against the experience of field personnel. The study consisted of two parts: 1) development of a GIS based model derived from the physical properties within 530 designated watersheds on private and state-owned commercial timberlands in California. The details of this system are discussed below, and 2) preparation and distribution of a questionnaire requesting information on suspected highly erodible watersheds. The questionnaire was completed by CDF Forest Practice Inspectors; engineering geologists with the DMG Timber Harvesting Plan Review Project; earth science professionals involved with reviewing Timber Harvesting Plans with the Regional Water Quality Control Board (RWQCB); and wildlife biologists with the California Department of Fish and Game (CDFG) involved with evaluating Timber Harvesting Plans. The watersheds identified from the questionnaire and review of existing data were cross checked with the information developed in the GIS model.

MODEL INPUT

Selection of Geomorphic Variables

The principal factors that have been shown to contribute to erosion in forested terrane are slope steepness, horizontal concavity, high groundwater, cohesionless soils, and weak bedrock (Durgin and others, 1989; Lewis and Rice, 1989; Peters and Litwin, 1983; Campbell, 1975). A total of 23 erosion-contributing variables were explored for potential use in the model during the design of this study. These include soil consolidation, soil permeability, soil depth, soil plasticity, colluvium depth, presence of surficial deposits, geology, vegetation, slope, slope length, slope aspect, land use, rainfall intensity, rainfall duration, seasonality of rainfall, temperature, landscape maturity dissection density, dissection depth, horizontal curvature, stream inner gorges, ground water table depth, and areas of potential rain-on-snow.

Some factors, such as changes in vegetation, areas and dates of land-use impact, rainfall duration, and rain-on-snow events are difficult to depict in map form due to their temporal variability. Many other of the above factors are not easily depicted in map form at regional scales, such as inner gorge development, stream dissection density and depth, ground water table levels, and horizontal curvature. Because all the areas in this study were forested, variability in vegetation type was considered to be minimal in terms of providing significant differences in ground coverage. Therefore, the project focuses on regionally consistent and available information over the entire study area. This includes geology (with the susceptibility of each geologic unit to landslide, debris slide, or surface erosion processes), slope steepness, and rainfall intensity (including mean-annual, 12-hour, and 2-hour precipitation).

Approximately 530 watersheds throughout northern California, each about 20,000 hectares, were evaluated in this study. Each watershed contains at least 25% private or state-owned commercial timberland. In each watershed, the physical attributes of slope, precipitation, and lithologic susceptibility to failure, were stratified into low, moderate, and high categories based on the relative contribution of that factor to erosion potential. These data layers were entered as

separate digital coverages in an ARC/INF0-based GIS. Rated polygons were area-weighted and additionally combined for each hydrologic basin. Although the relationships between these geomorphic factors no doubt are complex and non-linear, a simple linear additive relationship was used to combine data sets. The highly generalized nature of the input data, the averaging of data over watershed areas, and the lack of established empirical-relationships between the data cause the use of complex algorithms to give an improper impression of precision. The use of the additive data combination produces an array of ranked watersheds depicting those basins
which are theoretically most susceptible to accelerated hillslope degradation. Separate erosion-potential maps were generated for three general types of hillslope erosion: landslide, debris slide, and surface erosion.

Study Limitations

Any perturbation to a hillslope system may result in either a large or small erosional response depending on the balance of opposing tendencies preexisting at the site. For example, a hillslope may be steep and may be underlain by easily erodible regolith, but previous evacuation of material from the slope may have left little material available for transport (Figure 1). Similarly, an area of gentle slope may be deeply weathered and have excess material for transport, but land use practices may incur little erosion because the slope is gentle. Thus there is a complex interaction of multiple geomorphic variables which are in a constant state of apparent balance. This concept was summarized by Hack (1960), "A landscape is an open system which is in a steady state of balance with every slope and every form adjusted to every other." The large number of geomorphic variables controlling the evolution of a natural landscape creates a system which is difficult, if not impossible to evaluate empirically (Leopold and Langbein, 1962; Shreve, 1966, 1975; Smart, 1968, 1972). It is also difficult to predict how close a landscape is to a threshold condition before system disturbance (Bull, 1991).

For these reasons there are no established quantitative relationships between the factors controlling erosion. Although it is difficult to predict the response of a system to a change in land use, many scientists have noted qualitative cause and effect relationships. For instance a disturbance to a slope of moderate steepness on a specific geologic unit will tend to have accelerated erosion. Thus, an essentially qualitative model based largely on the field experience of numerous geologists and other resource specialists has been developed. The design and component input of the model is therefore limited to that of a highly simplistic and qualitative conceptual model.

Data Preparation

Watershed Boundaries

Approximately 530 watersheds, each about 20,000 hectares, were subdivided from preexisting sub-basins defined by the Hydrologic Basin Planning Areas of the RWQCB (1986). Land ownership maps were combined with forest coverage maps compiled by the CDF in order to define areas of private or state ownership with commercial timber. Only watersheds containing 25% or more private or state-owned commercial timberland were selected for this study. Tierra Data Systems provided GIS coverage of the 20,000 hectare watersheds used in this study. Previously existing watershed boundaries were used where possible, causing many watersheds to be administratively defined. Therefore, watershed boundaries are inconsistently represented across the region and do not always reflect individual hydrologic basins. Such watershed boundaries should not be used for scientific analysis; however, if aggregated into Hydrologic Sub-Basin Areas as defined by the RWQCB (1986), complete hydrologic basins are represented.

Slope

A digital slope map was produced for northern California using a derivative of a 3-arc second raster data set that was developed for the United States by the Army Map Service (now Defense Mapping Agency). The original data set was resampled to 150 X 150m pixel resolution by the U.S. Geological Survey (USGS) in Flagstaff, Arizona. This digital elevation model (DEM) was projected to a Lambert Conformable Conic projection with a central meridian of 119o W longitude. Although this data was carefully edited by the USGS, it retains numerous scanning artifacts contained within the original 3-arc second data.

To evaluate the accuracy of DEM slopes, slopes from selected locations were compared from measurements made in the field on topographic maps and from digital data with a 150m pixel resolution. These comparisons show that:

1. Field measurements are difficult to correlate accurately to topographic maps due to the complex microtopography in the field.

2. Although a comparison of digital slope measurements with topographic slopes shows a discrepancy at individual sites, a consistent relationship exists between digital slopes and topographic slopes when digital slopes are averaged over an entire drainage basin.

3. Digital slopes from random locations are up to 7% to 10% lower on average than topographic slopes (Figure 3).

4. Slopes are calculated in eight directions surrounding a central elevation. The steepest slope is assigned to a 150 x

150m pixel. This tie-limited spatial resolution of the digital slope calculations cause slopes less than about 300m in length to be measured inaccurately (Figure 4).

Geology

Qualitative evaluations of geologic material strength were developed from personal interviews with 21 professional geologists who have extensive experience with erosion in timber harvest areas in northern California (Table 1). The geologists were asked to classify the geologic units with which they were most familiar in terms of susceptibility to 1) landsliding, 2) debris sliding, and 3) surface erosion. Relative ratings of low, moderate, and high were assigned to each geologic unit (Table 2). To insure regional validity for the erosion values, geologists were asked to consider erosion responses on equivalent slopes, and to use their statewide knowledge of erosion susceptible lithologies when drawing comparisons for their specific area of expertise.

The geology data layer was digitized for generating the digital material-strength field for erosion analyses using a vector scan of scribed linework of the 1:750,000 scale geologic map of the State of California (Jennings, 1977). Line editing and polygon labeling were performed by USGS and DMG personnel at the USGS Western Regional Center, Menlo Park, California. Coregistered hydrologic features (coastlines, lake shorelines, and river channels) were also scanned to enable accurate coregistration with the DEM.

Precipitation

The precipitation data were manually digitized by DMG personnel from 1:1,000,000 scale blue line maps prepared for the CDF (1984). Digitized precipitation maps include, 1) mean annual precipitation (Rantz, 1969), 2) 12-hour intensity with a 50 year recurrence probability, and 3) 2-hour intensity with a 50 year recurrence probability. The location of isohyetal lines is highly generalized: rainfall data in the study area were- extrapolated from only 150 rain gages -- about one for every 1OO,OOOsq-km. In addition, few of these gages are in mountainous areas, so orographic effects have been estimated using manual techniques (U.S. National Weather Service, oral communication, 1993).

Analysis

To preserve the integrity of the DEM slope data, the Lambert Conic Conformable projection (119 central meridian) of the DEM data was adopted as the map projection for this project. The vector data layers (geology, precipitation, and watershed boundaries) were reprojected to this coordinate system. The Lambert Conic Conformable projection approximates the Albers Equal Area projection and therefore is well suited for applications of regional spatial analysis. The vector data layers (geology and precipitation) were rasterized to the level of precision of the digital elevation raster layer (150 X 150m pixels). To estimate the relative erosion potential of each pixel area, the raster data layers were added together within each pixel area according to the ranking scheme summarized in Tables 2 and 3. Separate analyses were calculated for each of the three major slope erosion categories - landslides, debris slide, and surface erosion. For each of these analyses the pixel values within each watershed were summed and averaged to calculate a rating value for each watershed. The results of these three erosion ratings were then added to estimate the total erosion potential for each watershed (Table 4). The highest possible theoretical rating is 9 where 100% of the watershed contains high geology, precipitation, and slope ratings. The highest rated watershed in our analyses is 7, and the average relative erosion rating is 4.

Systematic visual inspection of a digital overlay of stream channels, derived from a digital scan of hydrologic features coregistered with the geology scan and the 150 X 150m pixel DEM, indicates that the general locational precision of the various data layers falls within +300m or 2 DEM pixels (+0.6mm at 1:500,000 scale).

MODEL OUTPUT

Sources of hillslope sediment include landslides, debris slides, and surface erosion. Because the physical controls on failure for these three potential source types differ, they were modeled independently.

Landslides

Landslides modeled in this study include mass failures that have planes of failure that are relatively deep, generally greater than 3m, and have a fairly low width to depth ratio. The types of failures included in the landslide model are rotational and translational landslides (rock slumps, earth slumps, rock block slides, and earth block slides) and earth flows (Varnes, 1978). Many scientists have attempted to correlate deep-seated mass movement with the amount of precipitation; however, these studies show that the relationship is complex (Iverson and Major, 1987; Swanson and Swanston, 1977; Swanston, 1981; Campbell, 1975). Although the complex movement of subsurface water flow has thwarted attempts to use rainfall as a systematic predictor of landslide movement, most geomorphologists agree that the occurrence of deep-seated hillslope failure is related to seasonal precipitation (Brunsden, 1993; Jahns, 1969; Keefer and Johnson, 1983; Swanson and Swanston, 1977; Swanston, 1981).

The regional nature of this study, combined with the lack of empirical relationships between rainfall and landslide movement requires the use of a highly generalized rainfall distribution to model spatial patterns of relative ground saturation. Mean annual precipitation was chosen to provide a pattern of general rainfall for estimation of relative landslide potential. Low, moderate, and high ratings have been assigned to precipitation values to reflect resultant, and highly generalized landslide susceptibility categories (Table 3).

Likewise, the relationship between slope gradient and mass wasting processes is highly generalized due to the complexities of geologic, climatic, and land-use factors. For purposes of this model, steeper slopes are assumed to have a greater driving force with slopes from 10% to 30% being assigned a low value, 30% to 50% moderate, and steeper than 50% as high.

Geologic structure and lithology are significant factors predisposing certain terrane to mass movement. This trend is observed on geologic maps in California that show the majority of mapped landslides to be concentrated on a few geologic units. In some regions the overriding influence of lithology has created the basis-of landslide classification (Takada, 1964). The area of highest landslide propensity in the study area occurs in the central and eastern belts of the Franciscan Complex. Here melange and highly sheared and faulted sedimentary and metamorphosed sedimentary rock dominate. The mineralogic composition of the rocks causes them to be conducive to weathering and alteration to clay-rich material, becoming subject to extensive landslide and earthflow movement (Relsey, 1977). In fact, landsliding may be the dominant erosion process in the northern Coast Ranges.

Debris Slides

Debris slides modeled in this study include mass failures that have surfaces of failure that are relatively shallow, generally fewer than 3m, and have a fairly high width to depth ratio. The types of failures included in the debris slide model are rock, debris, earth falls and toples, debris slides, and debris flows (Varnes, 1978). Other terms used include debris torrents, mudflows, debris avalanches, soil flows, and soil slips (Cannon and Ellen, 1985; Campbell, 1975; Keefer and Johnson, 1983; Wieczorek, 1987; Ellen and others, 1993; Caine, 1980; Wentworth, 1943). Debris slides commonly occur where thin colluvial deposits blanket less permeable bedrock or soil material (O'Loughlin, 1972; Swanston, 1974; O'Loughlin and Pearce, 1976; Ellen and others, 1993). Once saturated, these deposits exceed the resisting forces and fail. Many studies have documented the predictive relationship between rainfall intensity and shallow debris flows (Campbell, 1975; Cannon and Ellen, 1985; Caine, 1980; Wieczorek, 1987). These studies note that antecedent water storage followed by a high intensity storm systematically triggers debris flows (Canon and Ellen, 1985).

Campbell (1975) and Wieczorek and Sarmiento (1983) indicate that 10 to 15 inches of antecedent seasonal rainfall is sufficient to set the stage for debris slides. Once field capacity of the soil mantle has occurred, a high intensity storm with extreme 1 to 24-hour precipitation can cause saturation and failure (Figure 2). For a 12-hour duration storm, a failure threshold has been shown to occur at a rainfall intensity of 0.2 to 0.4 inches/hour (Cannon and Ellen, 1985) and 0.25 inches/hour (Campbell, 1975; Caine, 1980). For this study rainfall intensities below 0.2 inches/hour were considered to be low and above 0.4 inches/hour were designated high. Isohyetal locations were obtained from a rainfall intensity map of California with a 12-hour duration and 50-year recurrence probability (CDF, 1984).

Many researchers have attempted to correlate debris slide occurrence with hillslope gradient. Shallow mass wasting typically occurs on steeper slopes than do deep-seated slides, with debris slides commonly occurring on slopes between 40% and 100% (Campbell, 1975; Sidle and others 1985; Durgin and others, 1989; Corbett and Rice, 1966; Rice and Foggin, 1971; Kesseli, 1943; Johnson and Sitar, 1990).

In northern and central California, low-cohesion material formed from weathered granite or sandstone bedrock shows the highest tendency for debris slide failure. In the Coast Ranges, the Redwood Creek and South Fork Mountain schists of the Franciscan terrane are highly susceptible to debris slides; in the Sierra Nevada and Klamath province, granitic plutons are commonly susceptible. However, mass wasting is limited to areas where hillslope detritus is available; steep slopes (over 100%) may be covered by little colluvium (Campbell, 1975)

Surface Erosion

In this study surface erosion includes sheetwash, ravelling, rilling, and gullying. An undisturbed forest in its natural pristine condition usually yields very little surface runoff (Dissmeyer and Foster, 1980). The forest ground cover (litter, logs, and rock) protects the soil from raindrop impact and surface runoff, creating infiltration rates which usually exceed rainfall intensity. However, land use impact resulting from mechanical site disturbance, (including road building, tractor yarding, site preparation, and fire) destroys vegetative cover, locally compacts the soil and exposes bare soil to the erosive energy of rainfall and runoff.

A few attempts have been made to quantitatively model approximations of surface erosion controlling factors in forested regions (Dissmeyer and Foster, 1980; California Soil Survey Committee, 1989). U. S. Department of Agriculture (USDA) (1978) identified six factors contributing to surface erosion in agricultural fields. However, the empirically derived relationships known as the Universal Soil Loss Equation (USLE) shows a poor correlation to sediment yield on forested hillslopes (Dodge and others, 1976). Part of this disparity results from the derivation of the USLE on gently sloping, finely textured agricultural fields, whereas forested landscapes are topographically, botanically, and lithologically diverse and thus difficult to model over large areas.

Three factors were chosen to approximate regiona1 susceptibility of forested hillslopes to surface erosion: a 2-hour high intensity rainfall storm with a 50 year recurrence probability slope, and lithologic potential for surface erosion. Soil loss per unit area generally increases in proportion to a power of hillslope gradient. In this study, surface erosion potential was rated low on 10% to 30% slopes, moderate on 30% to 50% slopes, and high on greater than 50% slopes.

Spatial Relations

Areas of steepest slope include the Klamath physiographic province and the deep canyons draining the west flank of the Sierra Nevada.

Mean annual precipitation is highest in northwestern California north of Eureka. Annual rainfall is moderate in the Coast Ranges north of Santa Rosa, in the Sierra Nevada Mountains, and in the Klamath province. Two-hour and 12-hour precipitation intensities show a generally similar distribution to mean annual precipitation with particularly high intensity rainfall over Arcata, Mount Shasta, and the Santa Cruz Mountains.

The general lithologic patterns in California roughly coincide with geomorphic provinces (Jenkins, 1938) and with tectonostratigraphic terranes (Auboiun and others, 1980; Irwin, 1966) (Figure 5). These include 1) the coastal Franciscan Complex, composed chiefly of Mesozoic and Cenozoic sedimentary and metavolcanic rocks which are highly sheared and deformed, 2) the Klamath crystalline basement complex consisting of highly metamorphosed Mesozoic and Paleozoic rock intruded by Mesozoic plutons, 3) the Cascade and Modoc provinces comprised of late Cenozoic and Quaternary volcanics, 4) and the Sierra Nevada Mountains cored by Mesozoic granite and granodiorite intruding metamorphosed Mesozoic and Paleozoic igneous and sedimentary roof pendants of the foothill region.

Erosion Potential

Watershed erosion ratings are high where one data layer is high and two out of three are either high or moderate. Therefore, although the Klamath province and the deep canyons of the Sierra Nevada are lithologically resistant, high precipitation and slope values give these areas high erosion ratings.

Of course, estimates of erosion potential generated for each pixel show greater geographic detail than estimates averaged over 20,000 hectare watersheds. This apparent detail, however, is somewhat misleading in that the detailed breaks between data units cause sharp contrasts which are not representative of actual field conditions. The generalized nature of individual data layers, combined with the uncertainty of geomorphic response furthermore causes imprecision of erosion values at specific locations. Only when erosion values are averaged over drainage basins do they accurately reflect the erosion potential.

Landslide Potential

The area of highest landslide potential exists in the Coast Range province, specifically in the eastern and central belts of the Franciscan terrane north of Clear Lake (Figures 5 and 6). Here, melange, clay-rich soil, and moderately steep slopes combined with moderate to high precipitation (100 to 250cm/yr) create unstable hillslopes. Landslide potential is generally low in the Sierra Nevada, with a few landslide-prone watersheds on the more clay-rich weathered metamorphosed Mesozoic and Paleozoic roof-pendant rock of the northern foothill region. In the Klamath province, landslide potential is highly variable, ranging from low to high with the highest potential occurring on the western side of the province where serpentinized ultramafic rock, steep slopes, and high precipitation create unstable hillslope conditions. Landslide potential in the Modoc and Cascade provinces is low, with only a few localized problem sites.

Debris Slide Potential

Debris slide potential is modeled as low to moderate in the Coast Ranges (low from the Santa Cruz Mountains to Santa Rosa, and moderate north of Santa Rosa) (Figure 7). In the Klamath province, debris slide potential is highly variable, ranging from low to high in a scattered pattern, while in the Cascade and Modoc plateaus debris slide potential is low. In the Sierra Nevada Mountains the potential is generally low with a few scattered watersheds having a moderate potential.

Surface Erosion Potential

Surface erosion ratings are low to moderate in the Coast Ranges, low to moderate in the Klamath province, and low in the Cascade, Modoc Plateau, and Sierra Nevada Mountains (Figure 8).

Total Erosion Potential

Total erosion potential combines landslide, debris slide, and surface erosion ratings within each watershed (Figure 9). The geographic distribution of relative erosion susceptibility shows a high potential in the northern coast ranges, moderate in the Klamath province, moderate to low in the Sierra Nevada Mountains, and low in the Cascade and Modoc Plateau physiographic provinces. This pattern of general erosion susceptibility is similar to that of the modeled landslide potential (Figure 6).

DISCUSSION

How well these modeled watershed values represent actual erosion potential is important if the watershed-rating maps are to be used for planning purposes. By understanding the limitations and uncertainties of the data used in this analysis, a more realistic use of the model can be facilitated. This will also aid in evaluating the accuracy of the model.

Four limitations contribute to the uncertainty of this analysis. First, geomorphic processes range widely, even in similar physiographic settings. In northern California, the inner-gorges of steeply sloping streams contribute significantly to total sediment yield within local watersheds (De la Fuente and Haessig, in review). Here steep stream canyon walls are cut into the toes of broad hillslopes. The undermined colluvium at the toe of the slope creates a continual cascade of weathered hillslope material into the streams. The break in hillslope gradient in these canyons suggests that the stream and hillslope systems are not in equilibrium, and that there has been a change in the rate of stream degradation at some point in the recent past. This allows a reservoir of hillslope material to be available for erosion.

Sediment transport from hillslopes to streams in many areas of the Sierra Nevada, however, operates quite differently. Here stream gorges are often bedrock walled and little or no colluvium is available for downslope transport. The process of grussification of granitic rock requires moisture to be retained at depth for prolonged periods of time. On steep slopes weathered material is rapidly removed, and a self-enhancing feedback loop occurs where bare rock does not retain moisture long enough to form crystalline detritus or gruss. Thus, in some of the deep, steep-sided gorges of the Sierra Nevada, little colluvium exists and, unlike the Coast Ranges, little sediment is available for stream transport. Slope steepness, then, by itself may not be a reliable indicator of erosion potential if no colluvial material is available for erosion.

Second, many workers have attempted to relate rates of sediment transport to landscape variables, yet understanding the relationship between geomorphic variables is incomplete. For this analysis a simple linear relationship between these variabilities was used. In reality these relationships are highly complex and involve the interactions of many variables not utilized in this analysis. Furthermore, the highly generalized nature of the input data, combined with the lack of empirically derived relationships between data sets, creates large uncertainties in the accuracy of the model. To structure the analysis in such a way as to assume precision between data sets would be to misrepresent the large uncertainties involved in the data relationships. It is therefore appropriate, and has been the consistent intent of this study, to keep all aspects of the model as simple as possible including the analysis, as it is based largely on the qualitative observations of landscape processes

Third, despite the unlimited number of factors affecting rates of hillslope erosion, this model uses only three factors: slope, precipitation, and, lithology. Although they are generally the most important under natural conditions, these three factors account for only a part of the variability in erosion potential.

Fourth, the data input into this analysis is highly generalized. The geologic units used at the 1:750,000 scale are amalgamations of several map units from larger scale maps. These units, in turn, commonly include a variety of lithologic types. The slope estimates are likewise inaccurate at less than a 300m grid. Precipitation data is furthermore derived from one gaging station every 1OO,OOOsq-km.

Developing ways to quantify, map, and integrate the variables that influence rates of erosion is a major challenge facing natural resource scientists. Although this model of relative erosion susceptibility is highly qualitative, it attempts to synthesize the physical attributes at a regional scale in California. To appraise the reliability of the model for identifying problem watersheds, three sources of data are examined: questionnaires inviting identification of known areas of erosion, published information on specific watershed studies, and suspended sediment yield data from large drainages.

Natural resource specialists working in timber-harvest-related activities were asked to identify watersheds that had potentially high rates of erosion (Table 5). Agencies responding to this questionnaire included the CDF, the RWQCB, the State Water Resources Control Board (SWRCB), DMG, and DFG. Nineteen responses were received identifying 121 watersheds distributed throughout most of the study area. To augment these observations, 32 studies of erosion in northern and central California were reviewed. These data are summarized in Figure 10 and Table 5.

The observed problem watersheds generally correspond with modeled watersheds having moderate to high ratings. Furthermore, the problem watersheds specifically correspond with modeled landslide potential rather than debris slide or surface erosion potential. In contrast, however, many of the erodible watersheds selected by modeling are not recognized as susceptible to accelerated erosion by field observations. Also, about 20% of those considered problem watersheds are in areas of extremely low ratings based on the model. Several reasons could account for this discrepancy. First, field observations may be incomplete or inconsistent. Second, land use impacts are not part of the intrinsic erosion potential model but may well be the primary factor creating observable erosion problems. Third, additional important factors such as inner gorge development, glacial history, and topographic maturity could add accuracy and detail to the resultant analysis.

Suspended sediment data support the general trends observed between the geomorphic provinces found in the erosion model. These data indicate that the Coast Range province in northwestern California is the most rapidly eroding area in the conterminous United States (Holeman, 1968; Curtis and others, 1973). These especially high erosion rates have been attributed to the lithologically unstable Franciscan terrane, geologically recent tectonism, high and distinctly seasonal precipitation, and major land use disruption. In contrast, the crystalline rock of the Klamath province is generally characterized by substantially lower mean annual suspended sediment yields than the Coast Ranges (Jones and others, 1972; De la Fuente and Haessig, in review). However, in the Sierra Nevada Mountains, suspended sediment yields are 30 times lower than averages from watersheds in the Coast Ranges (Nolan and Hill, 1991).

ADDITIONAL WORK

Additional data layers could enhance the erodible watershed inventory model by including information on land use history, soil properties, transient snow zone boundaries, geomorphic limits of inner gorge development, and areas of Pleistocene glaciation. The applicability of these data layers is described below.

Land Use

Land use activities can result in substantial increases in soil erosion. Clear cut timber harvesting and roading resulted in sediment yields 17 times higher than those in comparable unharvested basins in the Redwood Creek area of northwestern California (Janda, 1978). Although activities that directly increase erosion rates have been substantially reduced by Forest Practice Act regulations, the long term effects of past activities undoubtedly continue to influence sediment yields.

Digital land use data have been developed for California by the EROS Data Center, National Mapping Division, USGS and the University of Nebraska, Lincoln, using Advanced Very High Resolution Radiometry Imagery (AVHRP). Older land use files have also been published by the EROS Data Center as Land Use-Land Cover maps. These files could be used to identify where temporal changes in land use activities have occurred.

Soil Properties

The availability of weathered material is a critical component to erosion-potential mapping. The depth and grain size distribution of the regolith, however can be difficult to measure and varies widely even on homogeneous rock (Wahraftig, 1965). The USDA, Soil Conservation Service, has compiled digital coverage of soils for the state (STATSGO). Although highly generalized, it could be a useful data layer to supplement the lithologic component. Delineation of low cohesion soils may be useful for modeling surface erosion and debris slide potential, and high cohesion soils may provide further accuracy for modeling landslide potential. These models could then be compared to and adjusted to those defined by the geologic data. In addition, soil depth might be used for defining areas of hillslope sediment availability.

Transient Snow Zone

Within a given drainage basin, large storm events can mobilize material equivalent to many times the mean annual sediment yield (Janda and Nolan, 1979). In northern California, extreme runoff events typically result from high intensity tropical storms melting snow pack. It may be possible to delineate those areas where this phenomenon, known as the rain-on-snow-zone, could impact drainage basins. By using the methodology developed by the State of Washington (Green and others, 1993), a model could be developed that would define the boundaries of those areas most susceptible to rain-on-snow events.

Inner Gorge

Steep inner gorges contribute significantly to total sediment yield in many streams (De la Fuente and Haessig, in review). Areas containing these landform features could be outlined and added as another data factor.

Review of published literature, interviews with geologists and geomorphologists, aerial photographic interpretation, and field mapping will be required to identify boundaries separating regions where inner gorges are common from those areas where they are rare. Because of the complex nature of the tectonic processes that result in rapid watercourse base level changes, separating these areas will be time consuming and controversial.

Pleistocene Glaciation

Glacial scour has removed weathered hillslope material from areas of high elevation in the Sierra Nevada, Klamath, and Cascade physiographic provinces. Delineating areas of glaciation would further define watersheds with limited availability of weathered material.

Watershed-Scaled Analysis

A GIS-based model of erosion potential could be developed for a relatively small watershed to attempt to quantify erosion controlling factors. Detailed geomorphic mapping at a scale of 1:24,000 by DMG is in progress for three watersheds in northern California. A geology and geomorphology data layer combined with digital elevation data or a digital terrane model developed from aerial photographs could be used in conjunction with sediment yield data to define more detailed algorithms for sediment yield modeling.

Conclusion

The understanding of the relationship between geomorphic variables is complex and incomplete. As research on sediment yield, sediment transport, and geomorphology advances, the understanding of the relative significance of individual factors controlling erosion will be improved. The results of current and future research, in conjunction with the suggested further work, can be used to improve the quality of the erodible watershed inventory model.

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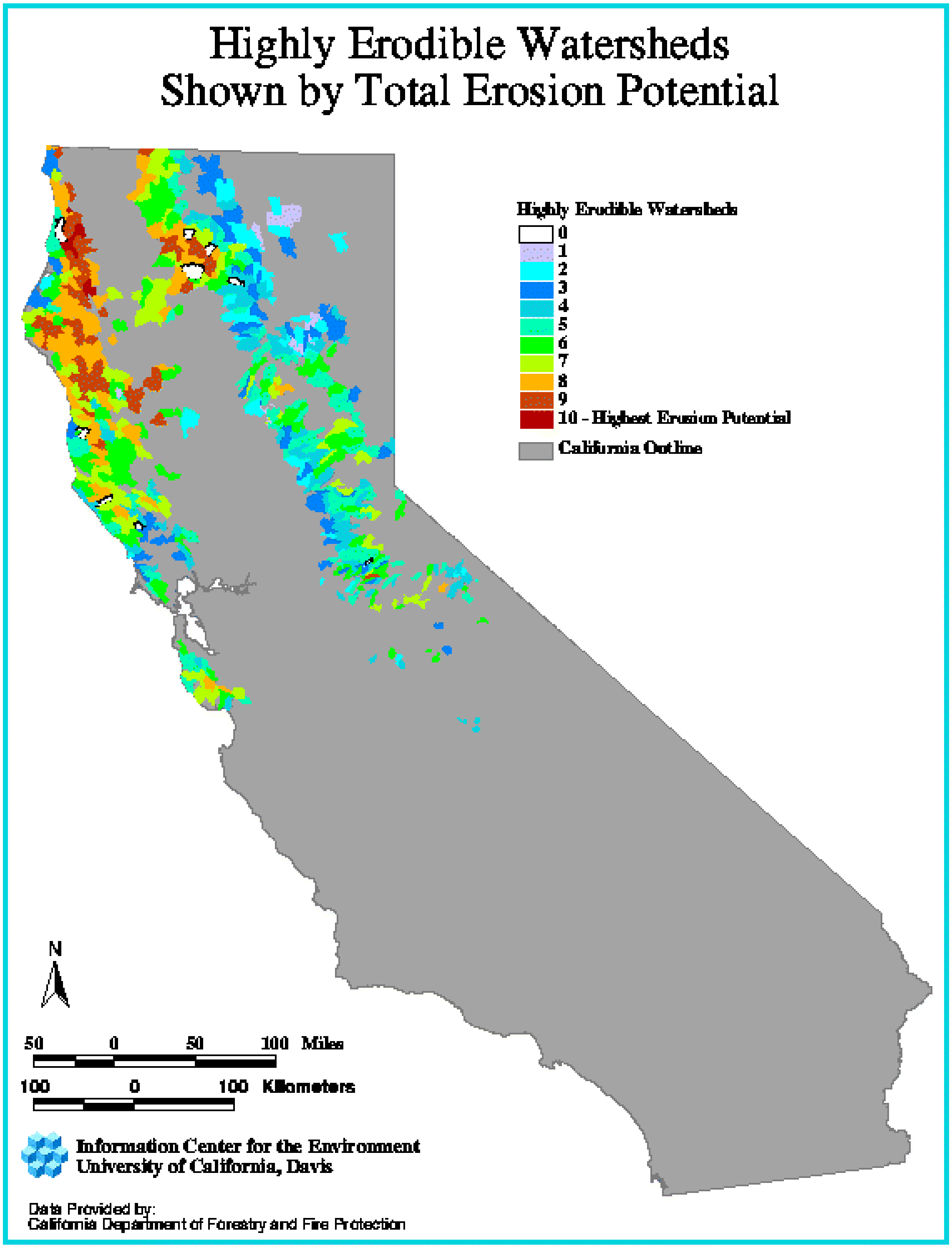
Highly Erodible Watersheds
Shown by Total Erosion Potential
Highly Erodible Watersheds
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10 - Highest Erosion Potential
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Information Center for the Environment
University of California, Davis
Data Provided by:
California Department of Forestry and Fire Protection